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A Pilot Study for Applying an Extravehicular Activity Exercise Prebreathe Protocol to the International Space Station

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Acronyms and Nomenclature

ALE	arm and leg (ergometer) exercise
bpm	beats per minute
DCS	decompression sickness
EVA	extravehicular activity
g	gravity
hr	hour
HR	heart rate
ISS	International Space Station
L/min	liters per minute
LE	leg-only (ergometer) exercise
min	minute
psia	pounds per square inch absolute
RPE	rate of perceived exertion
rpm	revolutions per minute
sec	second
TLE	tube and leg exercise
VO_2	oxygen consumption
VO_{2pk}	peak oxygen consumption
W	watts

Summary

Decompression sickness (DCS) is a serious risk to astronauts performing extravehicular activity (EVA). To reduce this risk, the addition of ten minutes of moderate exercise (75% VO_{2pk}) during prebreathe has been shown to decrease the total prebreathe time from four to two hours and to decrease the incidence of DCS. The overall purpose of this pilot study was to develop an exercise protocol using flight hardware (leg cycle ergometer and surgical tubing for arm exercises) and an in-flight physical fitness cycle test to perform prebreathe exercise before an EVA. Eleven subjects (6 men, 5 women; 38 ± 7 yr.; 68.5 ± 9.7 kg; 172.2 ± 6.9 cm) volunteered to participate in this study.

The first objective of this study was to compare the steady-state heart rate (HR) and oxygen consumption (VO_2) from a submaximal arm and leg exercise (ALE) session with those predicted from a maximal ALE test. The subjects performed a VO_{2pk} test using arm and leg cycle ergometers (2.75 ± 0.28 L/min) to determine the target VO_2 and HR values (2.06 ± 0.21 L/min, 155 ± 2 bpm) corresponding to 75% VO_{2pk}. During the submaximal exercise (2 minutes at 25% VO_{2pk}, three 1-minute stages at 38, 50, and 68% VO_{2pk}, and 5 minutes at 75% VO_{2pk}), 88% of the work was performed by the legs and 12% of the work was done by the arms. HR and VO_2 were averaged over the last 3 minutes of the 75% VO_{2pk} stage. Both VO_2 and HR during the submaximal ALE session were significantly greater than those predicted from the maximal ALE test ($p = 0.015, 0.028$).

The second objective was to compare the steady-state HR and VO_2 from a submaximal elastic tube and leg exercise (TLE) session with those predicted from the maximal ALE test. The submaximal TLE session was similar to the submaximal ALE 10-minute exercise, with 12% of the work done by the arms performing rhythmic contractions against surgical tubing. The predicted values were not significantly different from those measured during the submaximal tubing exercise ($p = 0.95, 0.42$).

The third objective involved a comparison of the maximal ALE test with a maximal leg-only (LE) test (2.67 ± 0.27 L/min) to conform to the in-flight fitness assessment test. The predicted submaximal VO_2 from the maximal LE test (2.00 ± 0.21 L/min) was not significantly different from that of the maximal ALE test. However, the 75% VO_{2pk} target HR from the LE test (150 ± 2 bpm) was significantly less ($p = 0.035$) than the target HR from the ALE test.

Prescribing exercise using data from the maximal ALE test resulted in the measured submaximal values being higher than predicted VO_2 and HR. Using a HR to control arm

exercise resulted in the target VO_2 and HR. However, the HR/VO_2 relationship during a maximal ALE test differs significantly from a maximal LE test. The HR predicted at 75% VO_{2pk} from the ALE test was higher (± 6 bpm) than the LE test. Therefore, to use the in-flight LE test to prescribe prebreathe exercise, the target HR may need to be adjusted slightly. The results of this pilot study suggest that elastic tubing is valid during EVA prebreathe as a method of arm exercise with the flight leg ergometer and it is recommended that prebreathe countermeasure exercise protocol incorporate this method.

Background

Decompression

Decompression sickness (DCS) results from the formation of microbubbles in tissues supersaturated with nitrogen (N_2) due to a decrease in ambient pressure. DCS is observed in divers upon return from depth to surface pressure and in astronauts who are exposed to lowered pressures during extravehicular activity (EVA). The pressure reduction from a normal cabin pressure of 14.7 psia to a suit pressure of 4.3 psia during EVAs exposes astronauts to a risk of developing DCS.

Symptoms of DCS vary depending upon the site of bubble formation (Moon, 1995). If located in the joints, pain may result from bubbles stretching tissues around nerve endings. "Chokes" are a result of bubbles forming in the capillaries in the lungs, causing shortness of breath or coughing. Bubbles may also form in central nervous system causing tingling, numbness, or paralysis. Skin mottling is also a symptom of DCS.

Breathing 100% oxygen (O_2) before decompression (preoxygenation) reduces the risk of DCS by washing nitrogen from tissues (denitrogenation). A period of prebreathing before EVAs involves crewmembers breathing an increased concentration of O_2 while ambient pressure is decreased. The need for multiple EVAs during the construction of the International Space Station (ISS) and tight mission schedules, causes increased concern for DCS and the appropriate protocols for preoxygenation.

Presently, two operational protocols exist for EVA prebreathe during Shuttle flights. The first protocol involves a staged decompression of the entire Shuttle. The first stage of this protocol is 1 hr of preoxygenation at 14.7 psia (Webb et al., 1996). The Shuttle is then decompressed to 10.2 psia for 12 hrs while the entire crew breathes a greater percentage of O_2 (26%). This is followed by an in-suit period of breathing 100% O_2 through the astronaut's helmet at 10.2 psia for 40 min before the astronaut decompresses to the final EVA suit pressure of 4.3 psia. This decompression protocol can last for as long as 36 hrs and requires a very large supply of onboard O_2. From an operational standpoint, a shorter protocol is critical to allow greater ease and speed when preparing for an EVA.

The alternative to whole cabin staged decompression is the second operational protocol of a 4-hr prebreathe with 100% O_2 while wearing the EVA suit. The Shuttle cabin remains at normal pressure of 14.7 psia. The major disadvantage to this protocol is that ISS will not have the capacity to store the quantity of O_2 necessary for such long prebreathe procedures. A second disadvantage is that the crewmembers dislike this protocol as it involves 4 hrs of inactivity. During Shuttle operations, whole cabin decompression is the preferred procedure as it provides more protection against DCS than the 4-hr prebreathe (Webb et al., 1996) and is the easiest for the crewmembers to perform. However, during ISS missions, it will not be feasible to carry enough O_2 to decompress the entire space station.

Exercise

Previous investigations have demonstrated that moderate exercise during prebreathe has a positive effect on denitrogenation. One example (Webb et al., 1996) was performed using a dual-cycle ergometer at a workload of 75% of each subject's peak O_2 consumption (VO_{2pk}). Webb et al. (1996) demonstrated that adding 10 min of dual-cycle ergometer exercise at 75% VO_{2pk} to a 1-hr prebreathe significantly reduced the incidence of DCS. DCS occurred in 77% of control subjects who performed no exercise during the prebreathe, but occurred in only 42% of the subjects in the exercise group. The positive effects produced as a result of moderate exercise extended beyond the time of exercise. The increased blood flow, combined with the 100% O_2 prebreathe, increased the rate of N_2 elimination during and following the time of exercise. In a separate study performed by Vann (1989), DCS occurred in 66% and 57% of seated and supine resting O_2 prebreathe subjects, compared to no incidents of DCS in subjects who performed moderate arm and leg exercise during prebreathe.

The findings of these studies indicate that the incorporation of moderate exercise into the prebreathe protocol may significantly reduce prebreathe time. Light exercise increases ventilation and the rate of perfusion of N_2 and other gases, therefore increasing the rate at which N_2 is washed from the tissues and lungs. The washout in muscles is considered "fast" compared to the washout in joints, where pain from DCS is commonly reported. The increase in muscle perfusion and temperature as a result of moderate exercise has been suggested to increase N_2 washout in these tissues. An exercise intensity of 75% VO_{2pk} may be great enough to increase ventilation, temperature, and perfusion, but may be moderate enough not to cause muscle soreness, fatigue, or bubble nucleation, which may impair EVA activities.

While moderate exercise has been demonstrated to decrease the incidence of DCS, severe exercise with high-impact forces appears to increase bubble formation, accelerate N_2 absorption in the tissues, and increase the risk of DCS (Vann, 1989). Ferris et al. (1951) demonstrated that heavy exercise in the upper or lower extremities during altitude exposure increases the incidence of DCS. When exposed to altitude (35,000 ft), bends occurred in 55% of the resting subjects.

When the subjects performed strenuous exercise during exposure, the incidents of the bends rose to 100% and the mean onset time of symptoms was reduced.

Therefore, it is currently believed (Webb et al., 1996) that for exercise to be effective in decreasing the time of prebreathe, it must be of moderate intensity, approximately 75% VO_{2pk}, and not impose sudden impact, which may increase bubble formation. Further the exercise should include as many muscle groups as possible to increase perfusion to all areas of the body. The increase in perfusion should increase N_2 washout from the tissues. The exercise should be of relatively short duration, less than 10 min, but long enough to increase blood flow and the rate of N_2 washout.

In-Flight Prebreathe Exercise

This experiment is part of a multicenter study to determine the effects of exercise on EVA O_2 prebreathe requirements and to establish an exercise protocol to be used during Shuttle and ISS operations. The protocol established by Webb et al. (1996) using a 75% VO_{2pk} exercise test was adapted by the multicenter study to incorporate an arm ergometer to perform arm exercises. Of the total workload, 88% was performed by the legs, and the remaining 12% performed by the arms.

Current plans for ISS include a standard medical operations physical fitness measurement test, with crewmembers performing an upright cycle exercise test preflight. This test is repeated after 14 days in flight, and then monthly, to determine changes in aerobic fitness levels. Since the cycle ergometer will be on board Shuttle and ISS flights as standard physical fitness assessment and countermeasure hardware, we propose to use this cycle during the EVA prebreathe. The small size of the flight cycle is ideal for limited available space on Shuttle and ISS. However, due to flight hardware constraints and available space in airlock, there is not available room for an arm ergometer. Therefore, we propose to use surgical tubing to perform the in-flight arm exercises.

The multicenter study and previous studies have not included 75% VO_{2pk} exercise sessions using surgical tubing to exercise the arms, or tube and leg exercise (TLE). Instead, these studies have only used the dual-cycle ergometer for maximal and submaximal exercise testing.

The 75% VO_{2pk} arm and leg exercise (ALE) workload and heart rate (HR) goals for EVA prebreathe exercise will have to be based upon the results of the most recent in-flight, leg-only exercise (LE) cycle test. The exercise prescriptions will be updated as changes in fitness levels are observed by the in-flight fitness evaluations. The LE cycle tests then must be used to predict the ALE workloads. We believe that this will provide a valid prediction, since the contribution of the arms in the maximal exercise test is only 12% of the total workload.

Study Objectives

The overall goal of the multicenter project is to develop an in-flight O_2 prebreathe protocol which requires only 2 hrs, incorporates moderate exercise, and provides effective protection against DCS. The overall goal of the present pilot study is to develop the methodology to prescribe and perform in-flight exercise during prebreathe in preparation for EVA. The specific objectives of the present study are:

1. To assess the exercise prescription methods used in our ongoing chamber studies. Specifically, we sought to validate the method to prescribe a 75% VO_{2pk} submaximal ALE workload from data obtained during a maximal ALE test.
2. During in-flight exercise with EVA prebreathe, an arm ergometer will not be available. Elastic tubing may be available for the arm exercise, but would not permit quantifiable exercise. Therefore, we sought to determine whether the prescribed whole body VO_2 could be attained by using a target HR to control arm exercise during the TLE session.
3. Current operation plans include LE cycle tests performed periodically to assess crew health and fitness. These tests may provide the only data available to prescribe exercise during EVA prebreathe. Therefore, we sought to compare submaximal HR and VO_2 predicted from an ALE maximal test to those predicted from a LE maximal test.

Hypotheses

1. We hypothesized that the VO_2 and HR predicted from a maximal ALE test would not be different from steady-state values at 75% VO_{2pk} during the submaximal ALE session.

2. We hypothesized that the steady-state VO_2 during the TLE prebreathe protocol, using HR to control arm exercise, will not be different from the VO_2 predicted from the maximal ALE test.

3. We hypothesized that, when data from a maximal test are used to establish a 75% workload, HR and VO_2 will not differ from the measured steady-state values.

Methods

Overall

Eleven healthy volunteers, six males and five females, were screened for participation using a modified Air Force Class III medical examination and a Bruce treadmill stress test. Subject characteristics are given in Table 1. All test protocols were approved by the Johnson Space Center Institutional Review Board. All subjects were briefed about the protocols and procedures of the study before testing began, and signed informed consent forms indicating understanding and acceptance. Each subject participated in four separate exercise sessions on separate days: two maximal tests followed by two submaximal sessions. The maximal exercise tests (one ALE and one LE) were performed in random order. The first submaximal exercise session using an arm and a leg ergometer was followed by a second submaximal session using the leg ergometer with surgical tubing. The protocols for the maximal aerobic capacity tests and the 75% VO_{2pk} dual-cycle session were the result of a multicenter agreement during a telecon dated February 12, 1998.

Table 1: Subject Characteristics

	Females (n=5)	Males (n=6)	Group (n=11)
Age (yr)	42 ± 5	35 ± 6	38 ± 7
Height (cm)	167.1 ± 4.9	176.5 ± 5.3	172.2 ± 6.9
Weight (kg)	63.9 ±7.2	72.3 ± 10.5	68.5 ± 9.7

Maximal Aerobic Capacity Test: Arms and Legs (ALE)

The subject was instrumented using a Quinton Q5000 (Quinton Instruments, Seattle, WA) three-lead electrocardiogram system to monitor cardiac rhythms. HR was recorded using a Polar Heart Rate Monitor (Polar Vantage XL, Port Washington, NY), every 15 sec. Expired gas concentrations and volumes were measured using a Quinton Qplex I (Quinton Industries, Seattle, WA) interfaced with a mass spectrometer (Marquette-1100, Marquette, Inc., St. Louis, MO) in 30-sec intervals. Subjects breathed through a two-way nonrebreathing valve (2700 Series, Hans Rudolph, Kansas City, MO).

The subject was seated on a cycle ergometer (Lode Excalibur Sport 1300W, Groningen, Netherlands). The seat height of the leg ergometer and the height of the table supporting the arm ergometer were adjusted so that the subject could comfortably reach the arm ergometer. The subject began pedaling both the leg ergometer and the arm ergometer simultaneously (Monark

Rehab Trainer model 881E, Varberg, Sweden), with a low workload at a 65-rpm cadence to become familiar with maintaining equal cadence for both ergometers. Thereafter, the test began at workloads described in Tables 2 and 3. These workloads were calculated so that approximately 88% of the total work was performed by the legs and the remaining 12% by the arms. The workloads on the leg ergometer were preprogrammed and the arm ergometer was controlled manually by the investigator. The workloads on both ergometers were increased after 2.5 min at each exercise level. The test was terminated when the subject reached volitional fatigue or could not maintain the required arm or leg 65-rpm cadence. During the final 30 sec of each stage, HR and rate of perceived exertion (RPE) using the Borg scale (6-20; Appendix) were recorded.

The O_2 consumption for each exercise stage was calculated from the average of the last two 30-sec VO_2 measurements collected in the last minute of each stage. VO_{2pk} was determined as the highest O_2 consumption over a 60-sec period, which typically occurred in the last stage of the maximal exercise sessions. Peak HR was considered to be the HR at VO_{2pk}.

O_2 consumption vs. HR and O_2 consumption vs. workload from the maximal ALE test were plotted using the values recorded at each stage. Examples of these are shown in Fig. 1. A linear regression was determined for each exercise graph. The slope and y-intercept of the lines describing these relationships were used to determine the total (arm and leg) workloads for each stage of the 75% submaximal LE session. These regressions also were used to predict the target HR and determine leg workloads for the submaximal surgical tubing session.

Table 2: Maximal Aerobic Capacity Test Protocol—Male

Stage	**Time** (min)	**Leg Load** (W)	**Arm Load** (W)	**Total Workload** (W)
1	0-2.5	75	11.3	86.3
2	2.5-5.0	125	18.7	143.7
3	5.0-7.5	175	26.3	201.3
4	7.5-10.0	225	33.7	258.7
5	10.0-12.5	275	41.3	316.3
6	12.5-15.0	325	48.7	373.7
7	15.0-17.5	375	56.3	431.3

Table 3: Maximal Aerobic Capacity Test Protocol—Female

Stage	Time (min)	Leg Load (W)	Arm Load (W)	Total Workload (W)
1	0-2.5	53	7.9	60.9
2	2.5-5.0	88	13.1	101.1
3	5.0-7.5	123	18.4	141.4
4	7.5-10.0	158	23.6	181.6
5	10.0-12.5	193	28.9	221.9
6	12.5-15.0	228	34.1	262.1
7	15.0-17.5	263	39.4	302.4

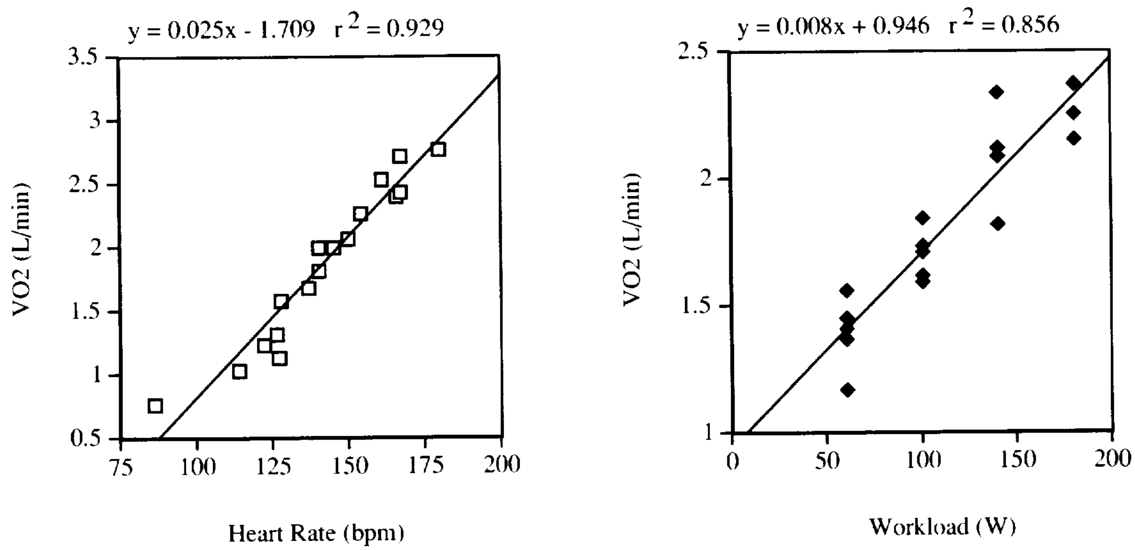


Figure 1: Relationship of HR vs. VO_2 and workload vs. VO_2 during maximal exercise testing.

Maximal Aerobic Capacity Test: Legs only (LE)

This maximal exercise test used the same protocol as the ALE maximal test, except that the total workload at each stage was equivalent to the leg workloads for the ALE maximal test. VO_2 and HR were measured with the same techniques as in the maximal ALE test.

HR vs. VO_2 and workload vs. VO_2 were plotted using the values recorded at each stage of the maximal LE test. Predicted values were not used in the prescription of any exercise sessions.

75% VO_{2pk} Submaximal Exercise Session: ALE

From the maximal ALE test data, submaximal workloads were calculated individually for each subject performing a 10-min test. The leg workload for each individual was programmed into the controller. The investigator manually set the setting on the arm ergometer at each stage. Leg exercise represented approximately 88% of the total workload, and the arm exercise was set to be 12% of the total workload.

The test consisted of a 2-min warm-up stage at a workload of 25% VO_{2pk}, a 3-min incremental stage (with increases of 12.5% VO_{2pk} each minute) and a 5-min exercise stage at a workload of 75% VO_{2pk}. These increments are shown in Fig. 2. The subject was instructed to maintain a 65-rpm pedal cadence on both the arm and leg ergometers for the entire test. VO_2 was calculated from the average of the last two 30-sec measurements in the last minute of warm-up and 75% VO_{2pk} stage or 30 sec of the 1-min increment stages. HR was reported and RPE were reported in the last 30 sec of every stage. VO_2 and HR were measured with the same techniques as in the maximal ALE test.

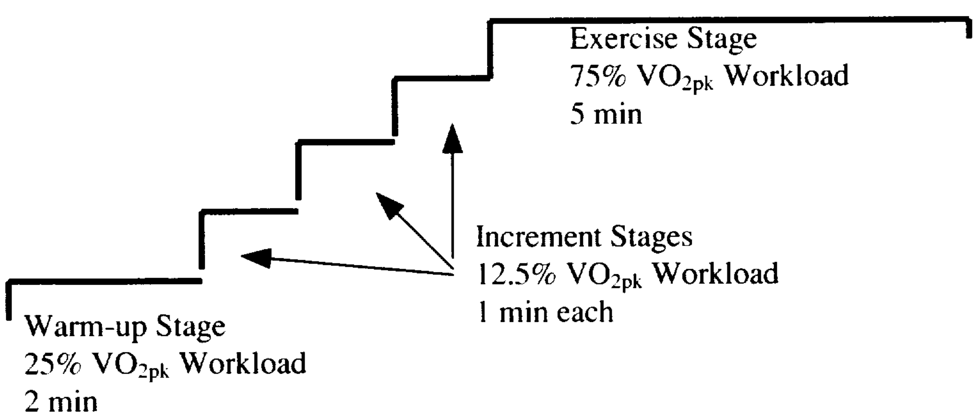


Figure 2: Submaximal workloads.

75% VO_{2pk} Submaximal Exercise Session: Surgical Tubing (TLE)

This exercise session was similar to the protocol used with the leg and arm ergometer. The leg workloads were the same but surgical tubing was used to provide arm exercise in place of the arm ergometer. The surgical tubing was attached to the handlebars of the leg ergometer and three thicknesses were available. The subject chose the thickness that would be the most comfortable for the exercise session. The subject was instructed to pedal the ergometer at a 65-rpm cadence while the cadence of the arm motion was recorded during a 10-sec interval of each stage. During each stage, the subject was instructed to increase or decrease the arm cadence and/or range of motion to maintain a target HR, which was based on the predictions from the ALE maximal test.

VO_2 and HR were measured with the same techniques as in the maximal ALE test. O_2 consumption was determined by the value of the last minute of each stage, or 30 sec of the increment stages. HR and RPE were recorded at the end of every stage.

Results

Submaximal ALE: Predicted vs. Measured

The mean VO_{2pk} during the maximal ALE test was 2.75 ± 0.28 L/min. Therefore, 75% VO_2 was calculated to be 2.06 ± 0.21 L/min. The steady-state mean VO_2 measured during the last 3 min of the 75% VO_{2pk} ALE test (2.23 ± 0.18 L/min) was significantly greater than the predicted VO_2 ($p = 0.015$). This relationship can be seen in Fig. 3 (Appendix).

The mean HR at VO_{2pk} during the maximal ALE test was 179 ± 2 bpm. The target HR predicted at 75% VO_{2pk} was 155 ± 2 bpm. The steady-state HR measured during the submaximal ALE test (165 ± 4 bpm) was significantly greater ($p = 0.028$) than the predicted HR. VO_2 and HR for the maximal and submaximal ALE sessions are given in Tables 8, 9, 12, and 13 (Appendix). Fig. 4 (Appendix) shows the HR measured in these tests.

Nine of the eleven subjects finished the submaximal ALE session. Subjects rated their overall exertion level at the end of the test to be between 12 and 14 on the Modified Borg RPE scale (Appendix). This indicates the test was "somewhat hard." The two subjects (3 and 6) who did not finish the test stated the reason for stopping the test was arm fatigue. These subjects rated their leg exertion as 9 and 12, but they rated the arm exertion as 18 and 19, respectively. This is a rating of "very hard" to "very very hard," indicating that perceived arm exertion was greater than perceived leg exertion. During the steady-state stage, these subjects reached a VO_2 of 1.27 ± 0.03 L/min and 1.66 ± 0.07 L/min, with a HR of 174 ± 7 bpm and 179 ± 1 bpm, respectively. The VO_2 and HR of subject 6 was actually 95% of VO_{2pk} and maximal HR, respectively. The submaximal VO_2 and HR of subject 3 was greater than the VO_{2pk} HR measured during the maximal ALE test.

75% VO_{2pk} Elastic Tubing Exercise: Predicted vs. Measured

During the last 3 min of the surgical tubing session, the mean VO_2 was 2.07 ± 0.19 L/min with a mean HR of 157 ± 3 bpm. The VO_2 and HR measured during the submaximal session were not significantly different from the predicted VO_2 ($p = 0.95$) and the target HR ($p = 0.42$). VO_2 and HR for the surgical tubing exercise session are given in Tables 16 and 17 and in Figs. 5 and 6 (Appendix).

The individual cadences for each subject varied from 18 to 108 ± 3 rpm during the last 3 min of the exercise of the surgical tubing test. The mean cadence was 70 ± 7 rpm. This is similar to the 65 rpm that subjects were asked to maintain on both the arm and leg ergometers during the ALE tests. Surgical tubing cadences for this test are given in Table 20 (Appendix).

All subjects finished the submaximal surgical tubing exercise session. Eight subjects rated their overall exertion level at the end of the test to be between 12 and 14 on the Modified Borg RPE scale (6-20). This indicates the test was "somewhat hard." One subject rated the test as 15 ("hard") and one subject rated the test as 9 ("very light"). All subjects indicated that this protocol would make a good warm-up before a hard workout.

Maximal ALE vs. Maximal LE

The mean VO_{2pk} during the maximal LE session was 2.67 ± 0.27 L/min, and 75% VO_{2pk} was calculated to be 2.00 ± 0.21 L/min. There was no difference between the ALE VO_{2pk} and the LE VO_{2pk}. Also, there was no difference between 75% VO_{2pk} predicted from maximal ALE and maximal LE ($p = 0.38$). This is shown in Fig. 7 (Appendix).

The peak HR during the maximal LE test (175 ± 2 bpm) tended to be less than the peak HR during the maximal ALE test ($p = 0.062$), but was not significant. However, the 75% VO_{2pk} HR calculated from the maximal LE test (150 ± 2 bpm) was different from the 75% VO_{2pk} HR calculated from the maximal ALE test ($p = 0.035$). The mean difference in the predicted HR between the ALE and LE test for the 75% VO_{2pk} stage was 6 ± 2 bpm. Peak HR measured during the maximal LE test is given in Table 5 (Appendix). The relationship between the maximal ALE and LE target HR can be seen in Fig. 8 (Appendix).

Discussion

The goal of this present pilot study was to develop the methodology to prescribe and perform in-flight exercise during prebreathe in preparation for EVA. We examined three specific objectives.

Submaximal ALE: Predicted vs. Measured

The first goal addressed was to assess the exercise prescription methods used in our ongoing chamber studies. We sought to validate a method to prescribe a 75% VO_{2pk} ALE session from data obtained during a maximal ALE test. We found that both VO_2 and HR during the steady-state stage of the ALE submaximal test were significantly greater than predicted from the maximal ALE. An exercise intensity of approximately 75% VO_{2pk} has been determined to be an ideal workload because it increases N_2 washout without increasing the risk of N_2 bubble formation and, therefore, increased risk of DCS (Webb et al., 1996). The steady-state VO_2 during the submaximal ALE session was measured at 83% of VO_{2pk}. We attribute the difference in the predicted and measured workloads to the arm ergometer. The workload settings on this ergometer are small and the accuracy of the settings is difficult.

All subjects rated the overall exercise as "somewhat hard," but two subjects stated that the arm exercise was much more difficult and rated the arm exercise as "very hard" to "very very hard." These two subjects also stopped the test before completion due to the difficulty of the arm exercise. A 75% VO_{2pk} workload for the arm ergometer for these subjects should not have produced an RPE of this magnitude. The VO_2 and HR responses indicate that these two subjects were working at an exercise intensity of greater than 75% VO_{2pk}.

75% VO_{2pk} Elastic Tubing Exercise: Predicted vs. Measured

The second goal was to determine whether the desired whole-body VO_2 could be attained from using a target HR to control arm exercise during the tubing exercise session. The use of HR to control the arm exercise intensity resulted in a VO_2 which was not different from the predicted value. Monitoring HR and adjusting arm cadence or length of stroke with the elastic tubing to maintain a desired HR at the prescribed 75% VO_{2pk} may provide adequate control over exercise intensity. This is opposed to our protocol, using the arm ergometer, where workload was prescribed for both arm and leg exercise and programmed into the ergometers for the exercise session and workload was maintained throughout the test.

The mean cadence for the surgical tubing test was 70 ± 7 rpm, which is similar to the 65-rpm cadence that the subjects were required to maintain on the dual-cycle ergometer. This suggests that the desired cadence for the elastic tubing is similar to that prescribed for the ergometers. The variability of the cadence across subjects can partly be attributed to the fact that the range of motion with the surgical tubing was not strictly controlled for each subject. Each subject found and maintained a particular arm motion that was the most comfortable. During in-flight prebreathe exercise, crewmembers will be able to develop an individual motion that is comfortable while still maintaining a target HR and VO_2. Crewmembers will be able to view a HR monitor display to maintain the target.

In this pilot study, we did not take into consideration the effect microgravity has on HR. Microgravity exposure causes loss of blood volume and headward fluid shifts, which may alter the VO_2/HR relationship. A loss of fitness may occur during flight, and this also would increase HR during prebreathe exercise. This will be accounted for during a mission by the fact that fitness evaluations to be used to prescribe the countermeasure target HR will be performed in microgravity, within 2 weeks of a scheduled EVA.

Maximal ALE vs. Maximal LE

The final goal was to compare submaximal HR and VO_2 predicted from an ALE maximal test to those predicted from a LE maximal test. The VO_2 and HR were consistently higher at each stage of the maximal ALE test than during the maximal LE test. The difference was expected due to the addition of arm exercise, representing an additional 12% of the total workload. The VO_{2pk} and the maximal HR for each test were not significantly different. This indicates that equivalent VO_{2pk} and maximal HR can be achieved by either a maximal ALE or LE test with these testing protocols.

The predicted 75% VO_2 calculated from the maximal LE and ALE test were not significantly different from each other. Using VO_{2pk} from either a maximal LE or ALE test to calculate a submaximal exercise leg workload should result in a similar desired workload and VO_2 during submaximal exercise. However, the total workload may be lower since the target HR used to control arm exercise, calculated from the maximal LE test, is significantly lower than the target HR calculated from the maximal ALE test.

The difference between the maximal ALE and LE target HR at the 75 % VO_{2pk} exercise stage is 6 ± 2 bpm. This difference, although significantly different, may not be large enough to affect the VO_2 produced during the submaximal exercise.

Limitations

Limitations of this study can be attributed to the following:

1. This is a pilot study for this equipment and these protocols. This study was to evaluate a protocol that could be used with the flight-certified exercise equipment currently scheduled to be flown on Shuttle and ISS.
2. The tests were performed on an upright cycle ergometer rather than the flight cycle. The semi-recumbent flight cycle is not designed for use in a 1-g environment and would be too uncomfortable.

3. This study was not performed in microgravity, which may alter the biomechanics and cardiovascular responses to exercise.
4. The subjects in this study were healthy and relatively fit. The subjects were not deconditioned by microgravity exposure as the astronauts may be when performing EVA prebreathe exercises. Cardiovascular and musculoskeletal changes due to spaceflight may influence the performance and/or the effectiveness of the prebreathe protocol.

Conclusions

- Based upon the findings of the ALE study, prescribing dual-cycle exercise based on the maximal ALE test resulted in higher-than-predicted VO_2 and HR.
- Based upon the findings of the surgical tubing ergometer study, using a target HR to control arm exercise resulted in the predicted VO_2 and HR.
- The HR/VO_2 relationship during a maximal ALE test was different from a maximal LE test. Therefore, the HRs predicted at 75% VO_{2pk} from each maximal exercise test were statistically different from each other, although the 75% VO_2 values were not different.

Applications of Findings

It may be reasonable to prescribe the prebreathe countermeasure exercise protocol from a LE test and to perform this countermeasure using the in-flight cycle ergometer with elastic surgical tubing for arm exercises.

References

Conkin J, Foster PP, Powell MR, Waligora JM. Relationship of the time course of venous gas bubbles to altitude decompression illness. Undersea and Hyperbaric Medicine 1996; 23(3):141-149.

Conkin J, Waligora JM, Horrigan DJ, Hadley AT. The effect of exercise on venous gas emboli and decompression sickness in human subjects at 4.3 psia. NASA Technical Memorandum 58278 1987; 1-15.

Ellestad, MH. Stress Testing. Principles and Practice. Philadelphia, PA: F.A. Davis Company: p. 58.

Ferris EB, Engel GL. The Clinical Nature of High Altitude Decompression Sickness. In: Fulton JF, ed. Decompression sickness. Philadelphia, PA: WB Saunders, 1951:4-52.

Heimbach RD, Sheffield PJ. Decompression sickness and pulmonary overpressure accidents. Fundamentals of Aerospace Medicine, Second Edition. Baltimore, MD; Williams and Wilkins, 1996.

Moon RE, Vann RD, Bennett PB. The physiology of decompression illness. Scientific American 1995; 70-77.

Shepherd RJ. Tests of maximum oxygen uptake: a critical review. Sports Med. 1: 99-124, 1984.

Vann RD. Exercise and circulation in the formation and growth of bubbles. In: Supersaturation and Bubble Formation in Fluids and Organisms (Brubbakk, Hemmingsen, Sundnes, eds.) 1989; 235-264.

Webb JT, Fischer MD, Heaps CL, Pilmanis AA. Exercise-enhanced preoxygenation increases protection from decompression sickness. Aviation, Space, and Environmental Medicine 1996; 67:618-624.

Appendix

Leg-Only Maximal Aerobic Capacity Test

Table 4: Oxygen Consumption in the Maximal LE Test (L/min)

Subject	Minutes												
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	0.23	0.56	0.82	0.89	0.89	0.87	0.98	1.23	1.18	1.28	1.31	1.37	1.47
2	0.23	0.51	0.83	0.90	0.89	0.92	1.01	1.11	1.40	1.38	1.27	1.34	1.63
3	0.23	0.48	0.66	0.67	0.72	0.72	0.84	0.84	0.92	0.96	1.03	-	-
4	0.23	0.6	1.28	1.08	1.06	1.03	1.39	1.36	1.57	1.57	1.85	1.91	1.97
5	0.23	0.72	0.94	1.25	1.27	1.21	1.33	1.45	1.69	1.73	1.80	1.90	2.18
6	0.23	0.6	0.76	0.95	0.92	0.96	1.04	1.10	1.28	1.34	1.34	1.39	1.55
7	0.23	0.81	1.19	1.41	1.44	1.24	1.49	1.68	1.84	2.03	1.97	2.12	2.18
8	0.23	0.91	0.95	1.04	1.10	0.95	1.11	1.17	1.27	1.31	1.31	1.45	1.63
9	0.23	0.49	0.89	1.02	1.14	1.14	1.21	1.41	1.53	1.63	1.66	1.75	1.94
10	0.23	0.98	1.16	1.33	1.45	1.59	1.64	1.84	2.12	1.99	2.15	2.16	2.43
11	0.23	1.03	1.34	1.51	1.56	1.57	1.66	1.94	1.97	2.14	2.11	2.25	2.53
Mean	0.23	0.70	0.98	1.10	1.13	1.11	1.25	1.38	1.52	1.58	1.62	1.76	1.95
SE	0.00	0.06	0.07	0.08	0.08	0.08	0.08	0.10	0.11	0.11	0.12	0.11	0.12

Subject	Minutes												MAX
	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	
1	1.56	1.60	1.83	1.85	1.96	1.98	-	-	-	-	-	-	1.98
2	1.53	1.71	1.73	1.87	1.96	2.13	2.00	2.17	2.22	2.26	2.36	2.42	2.42
3	-	-	-	-	-	-	-	-	-	-	-		1.03
4	2.14	2.29	2.43	2.47	2.55	2.78	-	-	-	-	-	-	2.98
5	2.35	2.54	2.48	2.65	2.91	2.96	3.24	3.24	3.28	-	-	-	3.28
6	1.55	1.67	1.65	1.52	-	-	-	-	-	-	-	-	1.67
7	2.43	2.55	2.89	2.81	3.27	3.18	3.06	3.93	-	-	-	-	3.93
8	1.72	1.80	1.67	1.98	1.99	2.05	2.23	2.24	2.33	2.44	2.47		2.47
9	2.07	2.20	2.34	-	-	-	-	-	-	-	-	-	2.34
10	2.59	2.69	2.79	2.87	2.92	3.06	3.26	3.35	3.29	3.71	-	-	3.71
11	2.66	2.86	2.83	2.89	3.15	3.17	3.30	3.54	3.50	-	-	-	3.54
Mean	2.06	2.19	2.26	2.32	2.59	2.66	2.85	3.08	2.92	2.80	2.42	2.42	2.67
SE	0.14	0.15	0.16	0.17	0.20	0.18	0.24	0.29	0.27	0.46	0.06	-	0.27

Table 5: Heart Rate in the Maximal LE Test (bpm)

Subject	Minutes 0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	75	90	103	102	107	107	121	131	136	144	146	154	158
2	-	118	119	119	121	119	125	128	136	136	140	146	150
3	97	112	128	138	142	145	155	162	164	170	175	-	-
4	84	108	118	114	115	126	137	135	138	141	146	154	161
5	62	76	92	90	98	94	103	106	108	112	113	122	129
6	94	110	116	123	124	127	140	151	156	160	162	168	174
7	70	93	107	111	116	117	119	129	135	138	137	143	147
8	95	112	108	108	105	107	112	116	122	119	120	129	137
9	75	92	99	103	106	110	116	122	126	132	135	140	146
10	85	104	110	109	111	114	121	129	127	137	133	139	145
11	80	114	116	118	121	122	123	133	133	135	140	141	142
Mean	82	103	111	112	115	117	125	131	135	139	141	144	149
SE	4	4	3	4	4	4	4	5	5	5	5	4	4

Subject	Minutes 6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	MAX
1	163	167	169	174	179	181	-	-	-	-	-	-	181
2	149	151	156	161	164	165	167	171	173	175	179	180	180
3	-	-	-	-	-	-	-	-	-	-	-	-	175
4	166	171	176	180	185	188	-	-	-	-	-	-	188
5	127	134	136	142	148	153	157	161	163	-	-	-	163
6	176	179	182	183	-	-	-	-	-	-	-	-	179
7	151	153	154	161	162	165	169	171	-	-	-	-	171
8	135	139	142	148	152	154	158	158	165	167	173	-	173
9	153	158	163	-	-	-	-	-	-	-	-	-	163
10	150	153	155	157	158	166	171	171	175	175	-	-	175
11	153	155	159	165	167	172	174	177	180	-	-	-	177
Mean	152	156	159	163	164	168	166	168	171	172	176	180	175
SE	4	4	4	5	4	4	3	3	3	3	3	-	2

Table 6: Ventilation in the Maximal LE Test (L/min)

Subject	Minutes 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	18.0	22.7	25.5	26.0	25.4	28.9	35.2	37.4	40.1	42.8	47.6	50.8
2	15.7	22.5	24.6	25.2	25.4	27.9	29.2	36.5	37.3	37.0	38.4	44.4
3	17.0	23.3	25.0	28.3	29.7	37.4	41.6	46.2	53.1	61.2	-	-
4	19.5	38.3	39.0	31.2	29.8	40.7	41.5	44.1	45.0	55.1	60.6	64.6
5	21.5	26.0	30.0	31.7	32.4	35.2	36.7	41.1	42.4	44.5	47.6	50.2
6	17.6	20.6	25.1	25.4	27.1	31.2	32.7	40.2	44.1	45.8	53.4	58.6
7	18.3	23.5	27.5	32.3	28.1	35.1	39.0	41.3	47.3	50.0	56.3	54.6
8	23.7	23.8	26.4	29.0	25.7	29.8	29.8	30.9	34.0	34.2	36.4	40.1
9	13.2	20.4	23.6	27.8	31.3	33.3	37.7	43.2	49.8	57.2	62.9	68.6
10	29.0	28.9	31.1	33.3	35.9	40.8	44.4	52.7	50.7	56.0	54.9	60.0
11	45.1	45.4	54.2	57.2	55.2	54.5	63.5	61.6	66.2	62.4	69.9	68.4

Subject	Minutes 6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
1	56.7	61.0	71.3	84.2	93.0	98.4	-	-	-	-	-	-
2	42.6	45.1	44.7	51.5	53.8	60.2	59.7	68.6	71.7	74.2	84.9	91.4
3	-	-	-	-	-	-	-	-	-	-	-	-
4	74.6	81.4	87.5	101.2	117.0	129.2	-	-	-	-	-	-
5	55.4	63.8	62.8	68.2	75.7	78.7	85.2	90.2	96.5	-	-	-
6	67.2	75.7	83.0	66.9	-	-	-	-	-	-	-	-
7	62.4	66.0	80.9	84.9	96.9	102.6	99.3	120.6	-	-	-	-
8	44.8	49.8	45.9	52.5	54.2	52.3	59.3	66.5	71.1	80.0	89.7	97.0
9	77.1	88.8	101.3	-	-	-	-	-	-	-	-	-
10	68.9	72.8	76.6	78.9	82.4	87.7	98.5	108.8	119.3	138.7	-	-
11	78.4	91.2	90.4	96.8	103.2	14.0	7.0	122.6	131.0	140.2	-	-

Table 7: Respiratory Quotient in the Maximal LE Test

Subject	Minutes											
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	0.80	0.75	0.81	0.84	0.84	0.87	0.88	0.97	0.97	1.00	1.01	1.02
2	0.90	0.83	0.88	0.92	0.92	0.91	0.89	0.89	0.96	0.97	0.98	0.97
3	0.81	0.95	1.06	1.17	1.22	1.29	1.38	1.43	1.50	1.53	-	-
4	0.85	0.98	1.21	1.09	1.02	1.03	1.13	1.05	1.12	1.12	1.15	1.17
5	0.86	0.86	0.92	0.97	1.02	1.03	1.04	1.05	1.08	1.07	1.08	1.03
6	0.80	0.79	0.82	0.89	0.92	0.95	1.00	1.07	1.13	1.17	1.19	1.23
7	0.68	0.69	0.73	0.84	0.86	0.88	0.89	0.91	0.96	0.98	1.02	1.01
8	0.83	0.86	0.93	0.97	1.01	1.02	0.98	0.99	1.03	1.03	1.03	1.03
9	0.85	0.80	0.89	0.97	1.06	1.08	1.09	1.17	1.24	1.33	1.34	1.34
10	0.91	0.87	0.82	0.82	0.83	0.89	0.88	0.92	0.95	0.98	0.97	0.97
11	1.13	1.02	1.05	1.07	1.04	0.95	0.95	0.97	0.98	0.98	1.00	0.92

Subject	Minutes											
	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
1	1.06	1.13	1.11	1.18	1.18	1.23	-	-	-	-	-	-
2	1.00	0.99	0.99	1.03	1.05	1.09	1.14	1.17	1.15	1.20	1.25	1.26
3	-	-	-	-	-	-	-	-	-	-	-	-
4	1.22	1.23	1.25	1.29	1.34	1.37	-	-	-	-	-	-
5	1.06	1.13	1.12	1.11	1.12	1.16	1.16	1.18	1.19	-	-	-
6	1.27	1.31	1.33	1.25	-	-	-	-	-	-	-	-
7	1.05	1.08	1.10	1.12	1.11	1.16	1.17	1.18	-	-	-	-
8	1.07	1.11	1.10	1.08	1.10	1.10	1.13	1.19	1.20	1.22	1.28	1.32
9	1.36	1.40	1.42	-	-	-	-	-	-	-	-	-
10	1.03	1.05	1.06	1.04	1.06	1.08	1.11	1.17	1.22	1.28	-	-
11	0.99	1.07	1.06	1.08	1.09	1.13	1.15	1.14	1.16	-	-	-

Arm and Leg Maximal Aerobic Capacity Test

Table 8: Oxygen Consumption in Arm and Leg Maximal Aerobic Capacity Test (L/min)

Subject	Minutes 0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	0.23	0.95	1.19	1.24	1.34	1.35	1.42	1.57	1.74	1.61	1.79	1.77	1.87
2	0.23	1.17	1.45	1.41	1.37	1.56	1.73	1.59	1.71	1.62	1.84	1.82	2.12
3	0.23	0.89	1.05	1.10	1.14	1.20	1.33	1.33	-	-	-	-	-
4	0.23	0.76	1.04	1.32	1.23	1.13	1.59	1.68	1.82	2.00	2.00	2.06	2.26
5	0.23	0.82	1.22	1.61	1.58	1.64	1.71	2.01	2.32	2.30	2.37	2.56	2.84
6	0.23	0.84	1.22	1.29	1.18	1.56	1.50	1.63	-	-	-	-	-
7	0.23	1.07	1.43	1.50	1.46	1.49	1.59	2.01	2.12	2.10	2.22	2.41	2.65
8	0.23	0.86	1.08	1.20	1.24	1.21	1.38	1.47	1.59	1.74	1.76	1.89	2.01
9	0.23	0.96	1.09	1.31	1.40	1.52	1.56	1.71	1.97	2.00	2.12	2.17	2.42
10	0.23	1.24	1.54	1.70	1.75	1.74	1.79	2.15	2.42	2.40	2.50	2.69	2.82
11	0.23	0.79	1.51	1.72	1.79	1.67	1.90	2.23	2.35	2.36	2.53	2.61	2.92
Mean	0.23	0.94	1.26	1.40	1.41	1.46	1.59	1.76	2.00	2.01	2.13	2.22	2.43
SE	0.00	0.05	0.06	0.06	0.07	0.06	0.05	0.09	0.10	0.10	0.10	0.12	0.13

Subject	Minutes 6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	MAX
1	2.00	2.01	2.06	-	-	-	-	-	-	-	-	-	2.06
2	2.33	2.08	2.08	2.25	2.37	2.15	-	-	-	-	-	-	2.37
3	-	-	-	-	-	-	-	-	-	-	-	-	1.33
4	2.4	2.43	2.54	2.72	2.76	-	-	-	-	-	-	-	2.76
5	2.88	3.11	2.88	3.28	-	-	-	-	-	-	-	-	3.28
6	-	-	-	-	-	-	-	-	-	-	-	-	1.63
7	2.63	2.91	3.00	3.26	3.42	-	-	-	-	-	-	-	3.42
8	2.20	2.21	2.25	2.28	2.39	2.55	2.63	2.50	-	-	-	-	2.63
9	2.52	-	-	-	-	-	-	-	-	-	-	-	2.52
10	3.06	3.16	3.29	3.23	3.56	4.10	3.62	4.27	4.32	-	-	-	4.32
11	2.86	3.23	3.16	3.44	3.61	3.77	3.78	3.96	-	-	-	-	3.96
Mean	2.54	2.64	2.66	2.92	3.02	3.14	3.34	3.58	4.32	-	-	-	2.75
SE	0.12	0.18	0.17	0.19	0.24	0.47	0.36	0.55	-	-	-	-	0.28

Table 9: Heart Rate in Arm and Leg Maximal Aerobic Capacity Test (bpm)

Subject	Minutes 0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	74	129	143	143	155	151	157	166	171	170	174	176	178
2	-	131	141	140	142	145	148	153	153	153	158	162	168
3	98	157	166	170	173	177	176	182	-	-	-	-	-
4	86	114	126	122	127	128	137	140	140	145	150	154	166
5	61	85	101	108	111	111	116	122	128	134	132	140	147
6	103	134	150	162	168	169	175	178	-	-	-	-	-
7	74	100	117	122	127	127	131	140	147	147	150	156	158
8	94	118	126	127	123	123	139	139	142	147	145	157	160
9	94	109	116	123	132	183	158	161	167	172	176	179	173
10	64	104	110	112	114	112	122	128	141	133	142	149	153
11	87	101	113	128	127	126	131	145	150	152	152	154	159
Mean	84	117	128	132	136	141	145	150	149	150	153	159	162
SE	5	6	6	6	6	8	6	6	5	5	5	4	3

Subject	Minutes 6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	MAX
1	179	180	180	-	-	-	-	-	-	-	-	-	180
2	170	170	170	173	174	175	-	-	-	-	-	-	174
3	-	-	-	-	-	-	-	-	-	-	-	-	182
4	167	161	167	180	191	-	-	-	-	-	-	-	191
5	152	155	156	162	-	-	-	-	-	-	-	-	162
6	-	-	-	-	-	-	-	-	-	-	-	-	178
7	165	166	170	172	177	-	-	-	-	-	-	-	177
8	162	164	164	171	175	177	179	178	-	-	-	-	179
9	167	-	-	-	-	-	-	-	-	-	-	-	167
10	156	155	160	167	168	170	174	177	181	-	-	-	181
11	164	168	169	172	176	181	182	185	-	-	-	-	185
Mean	165	165	167	171	177	176	178	180	181	-	-	-	178
SE	3	3	3	2	3	2	2	3	-	-	-	-	2

Table 10: Ventilation in Arm and Leg Maximal Aerobic Capacity Test (L/min)

Subject	Minutes 0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	22.1	29.4	33.8	39.4	41.6	46.8	56.2	63.8	66.8	74.2	80.6	82.5
2	31.5	43.7	41.6	40.3	46.6	46.9	46.5	53.3	50.7	54.9	56.2	66.0
3	32.1	39.4	45.0	52.1	54.9	68.2	74.5	-	-	-	-	-
4	25.3	31.7	44.0	41.8	34.9	52.8	52.7	60.0	73.3	73.8	83.1	97.5
5	24.9	31.9	39.3	40.0	42.2	44.5	46.2	55.4	57.8	56.7	68.5	73.1
6	30.2	42.0	48.3	49.7	61.3	70.3	84.0	84.1	-	-	-	-
7	26.4	33.2	35.9	38.3	40.4	41.7	53.0	57.9	60.7	63.2	65.5	78.0
8	23.1	26.6	29.1	30.8	30.5	36.5	38.4	42.4	42.6	48.1	50.7	52.0
9	22.3	25.3	31.0	35.9	41.8	45.1	47.6	56.5	64.8	71.5	80.6	90.6
10	31.0	38.9	44.1	46.1	46.9	48.0	54.3	63.4	65.4	68.3	74.7	78.5
11	30.8	43.4	55.0	52.8	51.3	57.0	72.8	71.9	78.6	80.1	84.9	96.9

Subject	Minutes 6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
1	87.2	90.4	88.9	-	-	-	-	-	-	-	-	-
2	75.5	70.3	70.1	82.0	901.0	83.1	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	102.1	109.0	108.4	131.8	154.8	-	-	-	-	-	-	-
5	77.5	82.3	78.1	93.6	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-
7	81.5	91.2	98.4	113.8	127.9	-	-	-	-	-	-	-
8	59.3	59.9	62.4	70.1	76.5	87.0	95.6	97.9	-	-	-	-
9	109.2	-	-	-	-	-	-	-	-	-	-	-
10	84.2	91.4	96.2	107.2	106.1	117.3	118.7	136.2	151.1	160.0	-	-
11	102.2	110.4	115.3	122.8	138.3	147.5	157.1	163.4	-	-	-	-

Table 11: Respiratory Quotient in Arm and Leg Maximal Aerobic Capacity Test

Subject	Minutes											
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1	0.75	0.80	0.89	0.95	0.98	1.00	1.04	1.11	1.15	1.15	1.17	1.18
2	0.86	0.96	1.01	1.03	1.04	0.98	1.04	1.11	1.11	1.07	1.10	1.10
3	1.03	1.11	1.23	1.32	1.31	1.36	1.43	-	-	-	-	-
4	0.97	1.00	1.12	1.23	1.16	1.18	1.16	1.20	1.30	1.28	1.27	1.29
5	0.91	0.91	0.94	1.00	1.02	1.03	0.98	1.05	1.10	1.08	1.10	1.11
6	0.92	0.94	1.06	1.15	1.18	1.29	1.35	-	-	-	-	-
7	0.75	0.80	0.83	0.91	0.93	0.93	1.00	1.03	1.08	1.06	1.03	1.07
8	0.92	0.90	0.92	0.95	0.96	0.98	0.98	0.97	1.00	1.04	1.03	1.02
9	0.79	0.86	0.93	1.03	1.10	1.15	1.15	1.21	1.28	1.32	1.33	1.36
10	0.86	0.90	0.94	0.97	0.99	0.99	0.96	1.01	1.03	1.04	1.05	1.08
11	0.96	0.89	1.01	0.99	1.03	0.99	1.05	1.04	1.08	1.06	1.06	1.08

Subject	Minutes											
	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0
1	1.19	1.19	1.16	-	-	-	-	-	-	-	-	-
2	1.16	1.19	1.18	1.20	1.22	1.22	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-	-	-
4	1.30	1.33	1.30	1.36	1.43	-	-	-	-	-	-	-
5	1.14	1.15	1.12	1.17	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-
7	1.14	1.15	1.15	1.19	1.22	-	-	-	-	-	-	-
8	1.04	1.04	1.07	1.10	1.13	1.17	1.20	1.21	-	-	-	-
9	1.40	-	-	-	-	-	-	-	-	-	-	-
10	1.07	1.11	1.10	1.14	1.07	1.00	1.16	1.17	1.20	1.24	-	-
11	1.11	1.11	1.12	1.11	1.15	1.17	1.19	1.18	-	-	-	-

75% VO_{2pk} Exercise with Ergometer

Table 12: Oxygen Consumption for Submaximal ALE (L/min)

Subject	Minutes 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	0.23	0.66	0.66	0.86	0.98	1.22	1.43	1.56	1.54	1.46	1.59
2	0.23	1.00	0.94	1.03	1.42	1.70	1.74	1.90	1.97	2.14	2.14
3	0.23	0.85	0.86	0.92	1.00	1.11	1.26	1.33	1.23	-	-
4	0.23	0.96	0.84	0.99	1.48	1.77	1.97	2.09	2.17	2.47	2.49
5	0.23	0.95	0.95	1.12	1.51	1.71	2.18	2.32	2.45	2.33	2.57
6	0.23	0.88	0.90	0.99	1.13	1.28	1.50	1.60	1.58	1.80	-
7	0.23	0.93	1.01	1.22	1.70	1.88	2.14	2.38	2.55	2.74	2.73
8	0.23	0.83	0.84	1.05	1.34	1.49	1.76	1.88	1.93	1.99	2.03
9	0.23	0.79	0.85	0.94	1.31	1.60	1.90	1.94	2.12	2.22	2.34
10	0.23	1.25	1.13	1.39	1.79	2.28	2.70	2.94	2.96	3.27	3.16
11	0.23	1.04	1.24	1.32	1.89	2.34	2.77	2.92	3.12	3.08	3.12
Mean	0.23	0.92	0.93	1.08	1.41	1.67	1.94	2.08	2.15	2.35	2.46
SE	0.00	0.05	0.05	0.05	0.09	0.12	0.15	0.16	0.18	0.18	0.17

Table 13: Heart Rate for Submaximal ALE (bpm)

Subject	Minutes 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	72	96	98	110	123	138	148	154	159	161	161
2	84	121	124	134	147	149	160	163	165	168	169
3	95	147	153	155	164	173	178	181	182	160	-
4	89	103	105	105	131	146	158	167	171	175	179
5	61	83	86	97	108	117	132	142	143	145	148
6	94	132	137	144	156	169	174	177	180	181	-
7	105	114	122	134	152	165	174	182	187	191	194
8	78	103	98	110	119	129	142	145	148	150	154
9	76	80	80	96	96	121	136	142	149	150	152
10	63	97	91	103	116	133	147	154	157	159	163
11	97	110	113	122	139	152	160	164	170	174	175
Mean	83	108	110	119	132	145	155	161	165	165	164
SE	4	6	7	6	7	6	5	4	4	4	5

Table 14: Ventilation for Submaximal ALE (L/min)

Subject	Minutes 1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	20.3	20.6	27.2	29.2	36.1	44.1	51.9	56.3	56.4	58.0
2	28.7	32.7	32.4	41.9	54.0	54.5	62.1	64.7	72.1	71.8
3	28.8	33.4	34.8	41.5	48.8	58.1	63.8	-	-	-
4	30.8	29.3	31.7	51.7	71.0	71.5	82.9	83.9	94.0	98.5
5	29.7	27.5	29.0	36.8	44.1	54.4	57.6	65.6	61.3	68.2
6	29.5	34.0	35.4	43.4	54.5	64.6	72.3	76.5	82.3	-
7	22.7	27.8	34.9	49.1	56.7	69.3	78.0	87.3	98.5	101.9
8	19.2	21.1	25.8	30.7	36.1	41.0	46.4	49.6	50.6	51.4
9	20.7	23.6	26.1	34.5	43.8	56.6	65.7	72.4	77.4	80.6
10	33.5	32.0	36.4	46.6	61.1	75.1	87.1	91.6	98.9	100.3
11	32.2	41.1	42.4	60.7	79.7	89.9	104.4	113.1	116.4	118.9

Table 15: Respiratory Quotient for Submaximal ALE

Subject	Minutes 1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	0.88	0.90	0.91	0.92	0.95	0.99	1.05	1.07	1.05	1.04
2	0.88	1.03	0.98	0.97	1.00	1.03	1.08	1.11	1.10	1.09
3	1.05	1.22	1.20	1.22	1.25	1.28	1.29	-	-	-
4	0.94	1.07	1.06	1.13	1.25	1.23	1.26	1.22	1.23	1.22
5	1.01	0.95	0.89	0.93	1.02	1.06	1.05	1.09	1.05	1.06
6	0.89	1.05	1.06	1.13	1.18	1.19	1.23	1.21	1.16	-
7	0.79	0.95	1.00	1.06	1.11	1.16	1.18	1.19	1.22	1.20
8	0.83	0.92	0.92	0.93	0.98	0.96	1.00	1.03	1.01	1.00
9	0.78	0.87	0.92	0.97	1.05	1.15	1.23	1.21	1.19	1.14
10	0.92	0.95	0.91	0.95	1.01	1.08	1.11	1.11	1.10	1.08
11	1.03	1.06	1.03	1.06	1.10	1.08	1.12	1.12	1.11	1.09

75% VO_{2pk} Exercise with Surgical Tubing

Table 16: O_2 Consumption for Surgical Tubing Submaximal Exercise (L/min)

Subject	Minutes 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	0.23	0.89	1.02	1.20	1.35	1.24	1.31	1.61	1.58	1.57	1.56
2	0.23	1.09	1.05	1.04	1.22	1.48	1.73	1.69	1.75	1.80	1.75
3	0.23	0.72	0.69	0.75	0.80	0.93	1.02	1.04	1.10	1.13	1.18
4	0.23	0.88	0.95	1.17	1.40	1.73	1.83	1.90	1.85	2.01	1.91
5	0.23	0.76	0.78	0.96	1.30	1.67	1.98	2.19	2.21	2.34	2.32
6	0.23	1.38	0.89	1.01	1.13	1.28	1.40	1.54	1.44	1.48	1.40
7	0.23	0.95	0.99	1.14	1.52	1.77	2.15	2.31	2.44	2.43	2.63
8	0.23	0.74	0.77	0.89	1.14	1.32	1.52	1.70	1.76	1.69	1.75
9	0.23	0.80	0.84	0.99	1.31	1.56	1.87	2.11	2.21	2.25	2.28
10	0.23	1.19	1.21	1.40	1.81	2.10	2.84	2.95	3.06	3.36	3.14
11	0.23	1.26	1.38	1.60	1.74	2.02	2.33	2.71	2.87	3.04	2.96
Mean	0.23	0.97	0.96	1.10	1.34	1.55	1.82	1.98	2.02	2.10	2.08
SE	0.00	0.07	0.06	0.07	0.09	0.11	0.15	0.17	0.18	0.20	0.19

Table 17: Heart Rate for Surgical Tubing Submaximal Exercise (bpm)

Subject	Minutes 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	83	112	119	129	132	145	147	154	154	154	154
2	71	117	113	122	128	136	147	148	148	147	150
3	99	138	138	137	143	153	156	156	158	160	161
4	86	101	102	110	129	148	162	162	167	169	172
5	61	85	80	92	103	116	129	131	132	136	137
6	83	132	119	126	134	141	141	154	155	155	152
7	80	115	115	127	142	151	164	172	172	172	172
8	89	101	101	114	122	133	145	148	150	151	153
9	63	88	92	102	115	124	136	145	150	157	161
10	73	96	97	108	124	135	151	161	162	165	166
11	89	103	105	114	130	137	148	155	159	168	171
Mean	80	108	107	116	127	138	148	153	155	158	159
SE	4	5	5	4	3	3	3	3	3	3	3

Table 18: Ventilation for Surgical Tubing Submaximal Exercise (L/min)

Subject	Minutes									
	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	27.9	32.5	38.9	45.9	49.2	52.4	67.0	68.0	73.0	75.0
2	31.0	31.8	30.2	33.9	39.5	48.2	49.8	50.3	53.0	50.9
3	27.9	27.7	29.0	31.5	37.1	43.0	46.1	46.5	49.4	51.2
4	24.9	29.5	33.9	47.6	70.4	70.3	79.2	82.0	83.3	80.7
5	19.6	19.7	24.0	31.0	41.1	51.2	54.9	56.2	56.2	58.1
6	44.2	32.9	34.7	36.9	43.6	48.6	53.3	50.4	50.3	50.7
7	23.0	25.9	29.8	38.0	48.5	62.8	73.4	80.6	81.1	88.4
8	18.6	21.3	23.5	29.2	35.7	43.2	47.3	49.4	46.6	48.8
9	20.6	22.9	27.7	40.0	48.5	63.1	77.2	84.3	88.9	95.8
10	33.1	35.4	37.8	50.5	66.1	90.9	101.7	104.9	106.7	103.5
11	40.4	45.5	51.1	64.8	67.7	82.5	94.9	104.7	117.5	116.5

Table 19: Respiratory Quotient for Surgical Tubing Submaximal Exercise

Subject	Minutes									
	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
1	0.85	0.93	0.98	1.00	1.08	1.07	1.09	1.09	1.10	1.08
2	0.85	0.92	0.90	0.92	0.92	0.98	1.03	1.00	1.00	0.99
3	0.94	1.04	0.98	1.05	1.07	1.12	1.13	1.11	1.09	1.09
4	0.93	0.99	0.97	1.10	1.26	1.21	1.29	1.27	1.23	1.16
5	0.87	0.87	0.89	0.91	1.04	1.07	1.08	1.06	1.03	1.02
6	0.92	1.07	0.99	0.96	1.03	1.07	1.11	1.10	1.08	1.07
7	0.76	0.87	0.88	0.91	1.02	1.10	1.18	1.17	1.16	1.14
8	0.80	0.87	0.85	0.87	0.91	0.95	0.98	0.97	0.98	0.96
9	0.87	0.97	1.00	1.13	1.13	1.19	1.26	1.25	1.25	1.23
10	0.91	0.95	0.91	0.95	1.01	1.08	1.15	1.11	1.10	1.05
11	0.91	0.89	0.97	1.10	1.07	1.12	1.16	1.15	1.13	1.11

Table 20: Cadence for Surgical Tubing Submaximal Exercise (rpm)

Subject	Minutes 1	2	3	4	5	6	7	8	9	10	Tube Thickness
1	-	42	102	60	66	60	66	72	72	72	Thick
2	102	102	96	96	90	84	102	90	96	114	Medium
3	36	33	33	30	27	21	15	18	18	18	Thin
4	72	72	72	78	72	72	72	72	72	72	Medium
5	-	27	36	63	66	72	-	72	72	72	Medium
6	60	36	36	36	36	69	69	69	72	72	Thin
7	72	72	72	72	66	66	66	60	48	36	Medium
8	69	66	72	72	72	-	66	66	78	-	Medium
9	72	72	72	72	84	102	96	114	102	108	Medium
10	72	72	72	72	78	78	72	72	72	72	Medium
11	72	72	72	72	60	66	66	66	66	72	Medium
Mean	70	61	67	66	65	69	69	70	77	71	
SE	6	7	7	6	6	7	7	7	10	9	

Table 21: Predicted 75% VO_2 and HR vs. Measured 75% VO_2 and HR

Subject	Predicted 75% VO_2 from Leg Max Test	Predicted 85% HR from Leg Max Test	Measured Tube Max VO_2	Measured Tube Max HR
1	1.48	152	1.61	154
2	1.79	158	1.80	150
3	0.60	149	1.18	161
4	2.00	161	2.01	172
5	2.45	135	2.34	137
6	1.25	155	1.48	155
7	2.63	150	2.63	172
8	1.84	144	1.76	153
9	1.70	137	2.28	161
10	2.63	150	3.36	166
11	2.64	154	3.04	171
Mean	1.91	150	2.14	159
SE	0.18	2	0.18	3

Table 22: Modified Borg RPE Scale

6	
7	Very, Very Light
8	
9	Very Light
10	
11	Fairly Light
12	
13	Somewhat Hard
14	
15	Hard
16	
17	Very Hard
18	
19	Very, Very Hard
20	

Figure 3: Maximal, Submaximal, and Predicted VO2

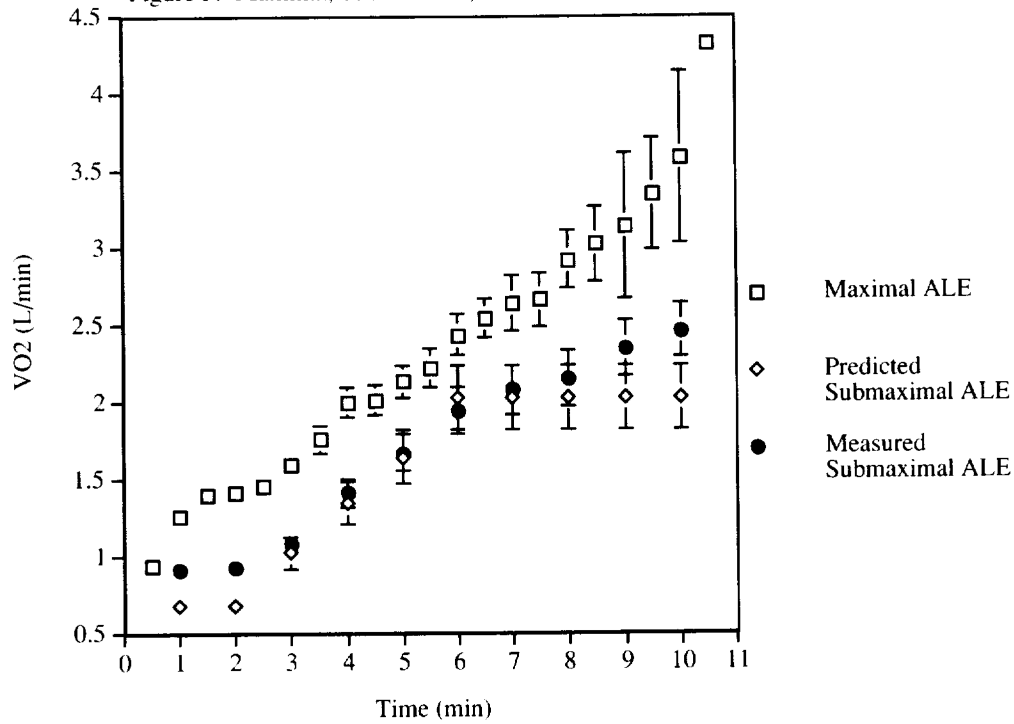


Figure 4: Maximal and Submaximal ALE, and Target Heart Rate

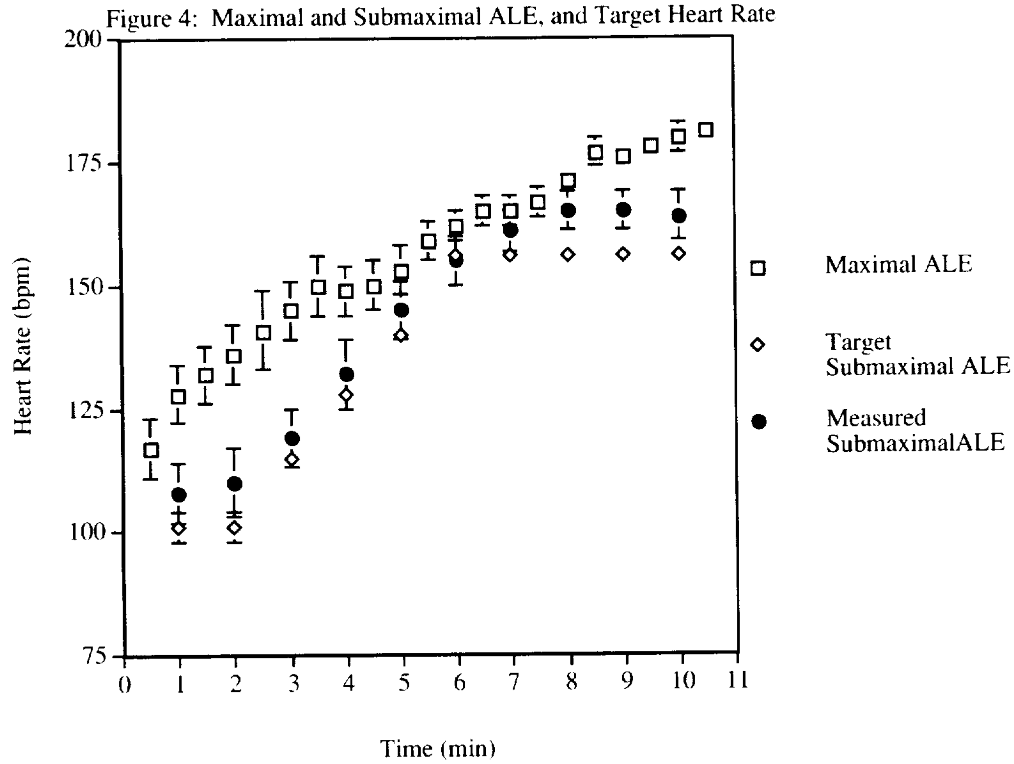


Figure 5: Maximal, Submaximal, and Predicted VO2

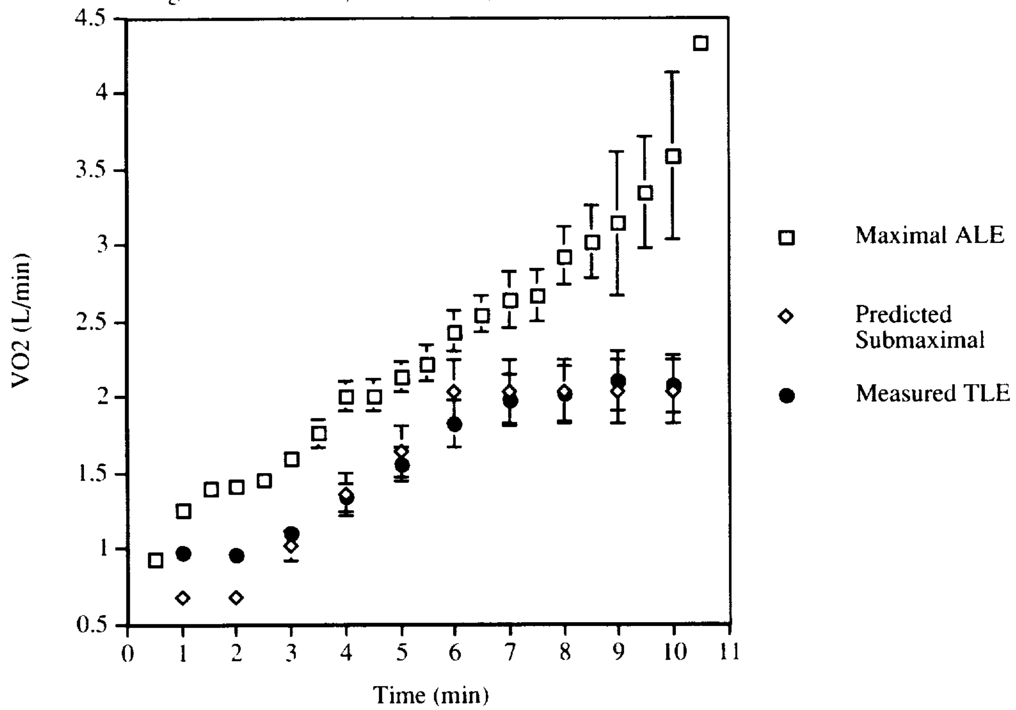


Figure 6: Maximal, Submaximal, and Target Heart Rate

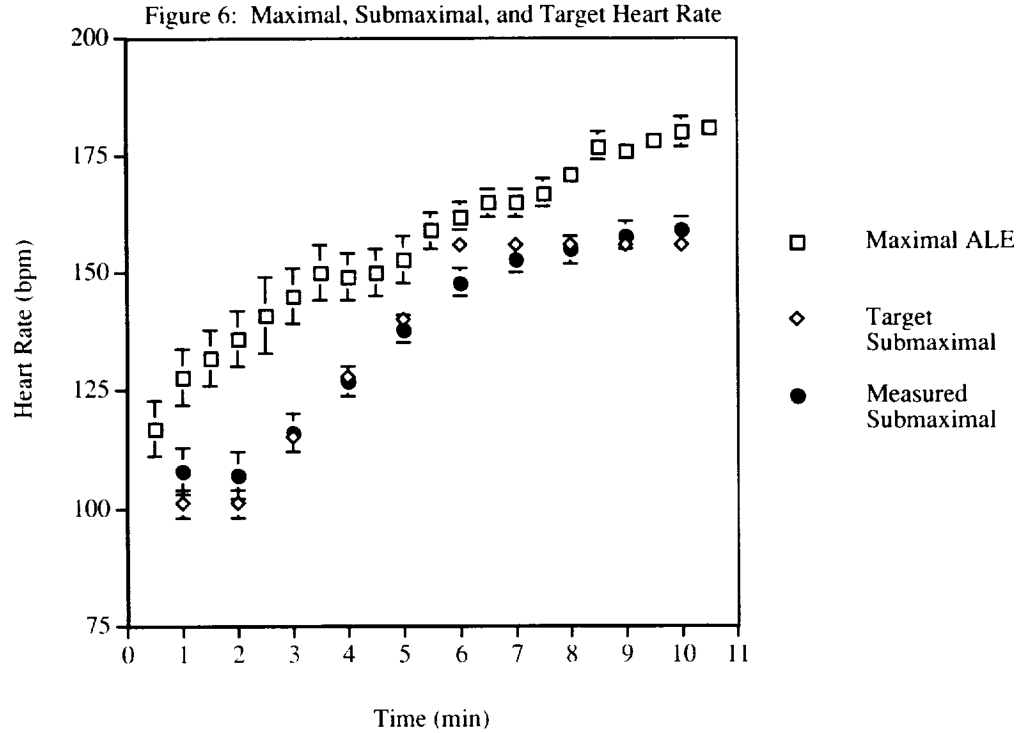


Figure 7: Predicted VO2 from ALE and LE

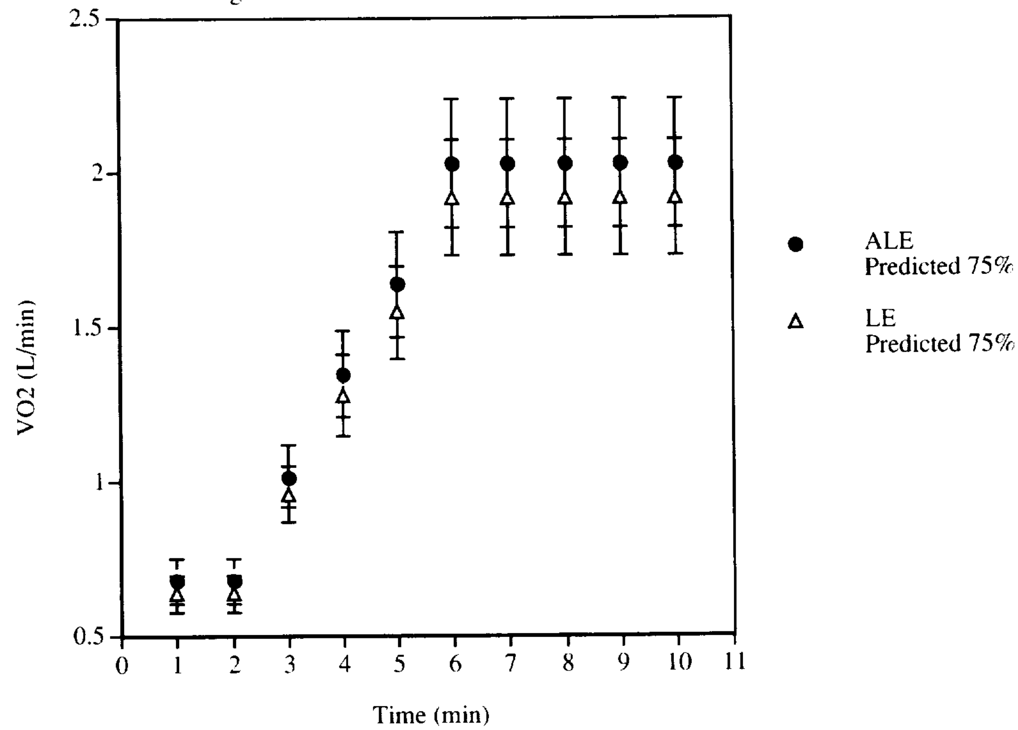
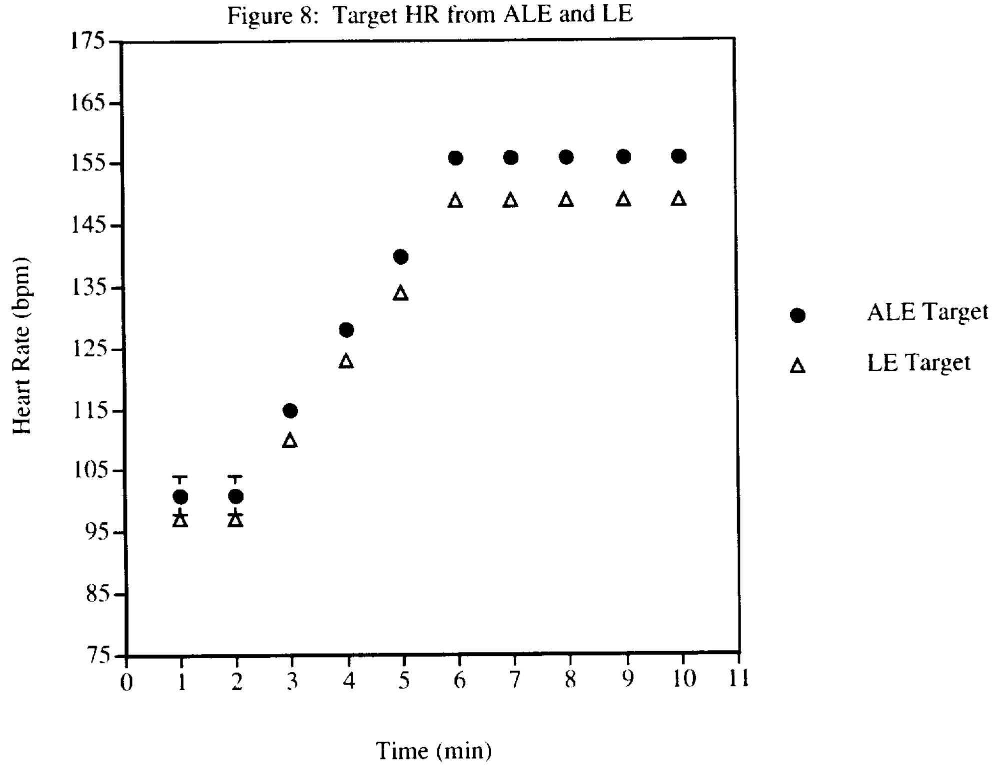


Figure 8: Target HR from ALE and LE



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A Pilot Study for Applying an EVA Exercise Prebreath Protocol to the International Space Station

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13. ABSTRACT *(Maximum 200 words)*
Decompression sickness (DCS) is a serious risk to astronauts performing extravehicular activity (EVA). To reduce this risk, the addition of ten minutes of moderate exercise (75% VO2pk) during prebreathe has been shown to decrease the total prebreathe time from 4 to 2 hours and to decrease the incidence of DCS. The overall purpose of this pilot study was to develop an exercise protocol using flight hardware and an in-flight physical fitness cycle test to perform prebreathe exercise before an EVA. Eleven subjects volunteered to participate in this study.

The first objective of this study was to compare the steady-state heart rate (HR) and oxygen consumption (VO2) from a submaximal arm and leg exercise (ALE) session with those predicted from a maximal ALE test. The second objective was to compare the steady-state HR and VO2 from a submaximal elastic tube and leg exercise (TLE) session with those predicted from the maximal ALE test. The third objective involved a comparison of the maximal ALE test with a maximal leg-only (LE) test to conform to the in-flight fitness assessment test. The 75% VO2pk target HR from the LE test was significantly less than the target HR from the ALE test.

Prescribing exercise using data from the maximal ALE test resulted in the measured submaximal values being higher than predicted VO2 and HR. The results of this pilot study suggest that elastic tubing is valid during EVA prebreathe as a method of arm exercise with the flight leg ergometer and it is recommended that prebreathe countermeasure exercise protocol incorporate this method.

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